

Flavour physics with a 4th generation

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We present an overview of recent work on flavour physics in the presence of a sequential fourth generation. We will discuss shortly the constraints on the new parameters and in the remainder present predictions for observables like $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$, $\text{Br}(K \rightarrow \pi \nu \bar{\nu})$ and the indirect CP violation $S_{\psi\phi}$ in the B_s system. We will further stress the importance of ε'/ε as a possible constraint once reliable lattice results for B_6 and B_8 become available. Lepton flavour violation is also briefly discussed in view of prospects for τ physics at an upgraded flavour factory as well as upcoming experiments for $\mu \rightarrow e \gamma$ and $\mu - e$ conversion in nuclei.

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1 Introduction

One of the most simple extensions of the Standard Model (SM3) is the addition of a sequential fourth generation (4G). This model is one the one hand highly restricted by near three generation unitarity as well as electroweak precision tests [1, 2, 3] and $\Delta F = 2$ observables [4, 9, 10]. On the other hand still leaves room for sometimes huge effects in soon to be measured observables. The generalisation of the CKM matrix to four generations yields five new parameters $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{14}, \delta_{24}$. Together with the two new quark masses this gives a total of 7 new parameters in the quark sector. In the lepton sector the new mixing angles are highly restricted through an interplay of bounds from rare μ and τ decays and their measured lifetimes [13, 12]. The recent efforts in studying flavour physics in the presence of a fourth generation [4, 5, 6, 7, 8, 9, 10, 11, 12] show clearly that in spite of its few new parameters the SM4 can not be excluded yet. In figure 1 we show on the left panel the correlation of

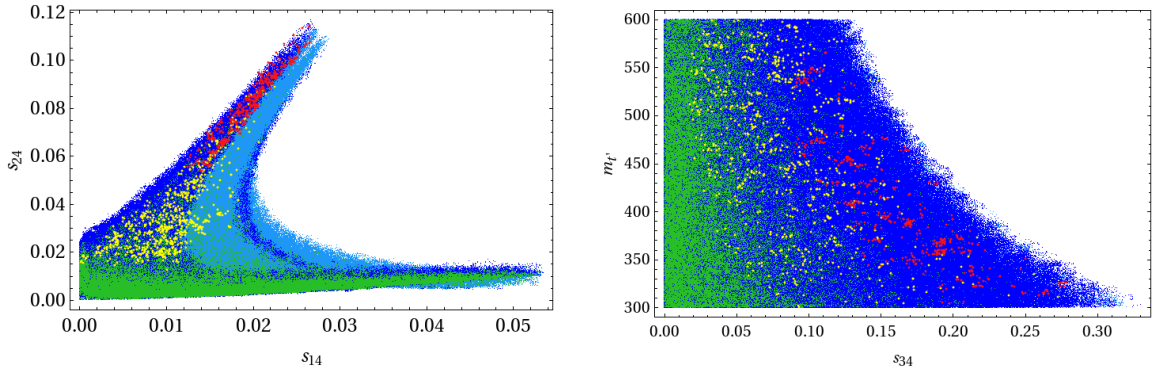


Figure 1: s_{24} vs s_{14} (left panel) and $m_{t'}$ as a function of s_{34} (right panel) both show how constrained the new parameters are.

s_{14} and s_{24} , this strong correlation is due to the directly measured CKM elements, Kaon physics and electroweak precision measurements [1, 10]. On the right panel of figure 1 we show $m_{t'}$ as a function of s_{34} this correlation can be directly linked to the constraint coming from the T parameter [1, 2, 3]. For the global analysis we use the convenient colour-coding specified below and in table 1. The large black point represents the SM3. Light blue and dark blue points stand for the results of our global analysis of the SM4 with the following distinction: light blue stands for $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) > 2 \cdot 10^{-10}$ and dark blue for $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 2 \cdot 10^{-10}$.

2 Rare Decays and CP violation

With the data collected till the end of 2011, the LHC experiments will be able to exclude $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ down to nearly the SM3 value. This of course prompts

	BS1 (yellow)	BS2 (green)	BS3 (red)
$S_{\psi\phi}$	0.04 ± 0.01	0.04 ± 0.01	≥ 0.4
$\text{Br}(B_s \rightarrow \mu^+\mu^-)$	$(2 \pm 0.2) \cdot 10^{-9}$	$(3.2 \pm 0.2) \cdot 10^{-9}$	$\geq 6 \cdot 10^{-9}$

Table 1: Three scenarios for $S_{\psi\phi}$ and $\text{Br}(B_s \rightarrow \mu^+\mu^-)$.

for the analysis of this decay in the context of models beyond the SM3. In figure 2 we show $\text{Br}(B_s \rightarrow \mu^+\mu^-)$ in correlation with $\text{Br}(B_d \rightarrow \mu^+\mu^-)$ and $S_{\psi\phi}$. There are two interesting features. On the left panel we find a anti-correlation between

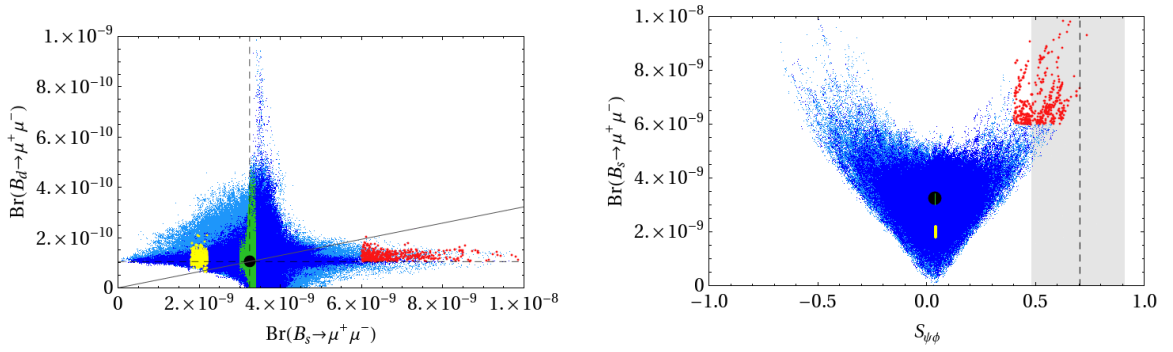


Figure 2: $\text{Br}(B_s \rightarrow \mu^+\mu^-)$ in correlation with $\text{Br}(B_d \rightarrow \mu^+\mu^-)$ (left panel) and $S_{\psi\phi}$ (right panel).

$\text{Br}(B_s \rightarrow \mu^+\mu^-)$ and $\text{Br}(B_d \rightarrow \mu^+\mu^-)$, which allows for any of the both branching ratios to be above or below the SM3 expectation but not simultaneously. On the right panel we find a strong dependence of $\text{Br}(B_s \rightarrow \mu^+\mu^-)$ on $S_{\psi\phi}$ in the case of a big $S_{\psi\phi}$. Additionally we note that for a suppressed $\text{Br}(B_s \rightarrow \mu^+\mu^-)$ we expect $S_{\psi\phi}$ to be SM3 like. Another upcoming experiment (NA62) intends to measure $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ to an accuracy of roughly 10%. In figure 3 we show $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ as a function of $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$. $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ can be enhanced by orders of magnitude above the SM3 expectation which implies an automatic enhancement of $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$. However the reverse is not true, $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ can be enhanced while $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ stays at its SM3 value or even below. The cut in $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ on the lower axis is due to $\text{Br}(K_L \rightarrow \mu^+\mu^-)_{\text{SD}}$.

2.1 The importance of ε'/ε

The ratio of direct over indirect CP violation the neutral Kaon decays is well measured but theoretical predictions suffer from hadronic uncertainties parametrised by R_6 and R_8 . To address the issue of the two unknown parameters we chose four different scenarios for (R_6, R_8) and studied the effect ε'/ε could have as a constraint on the

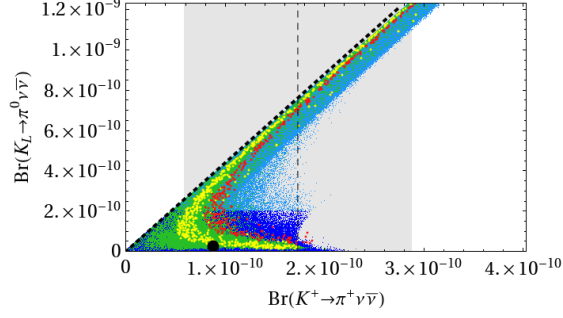


Figure 3: $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ as a function of $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$. The dotted line corresponds to the model-independent GN bound.

SM4. In figure 4 we show the impact of ε'/ε as a constraint on the correlations

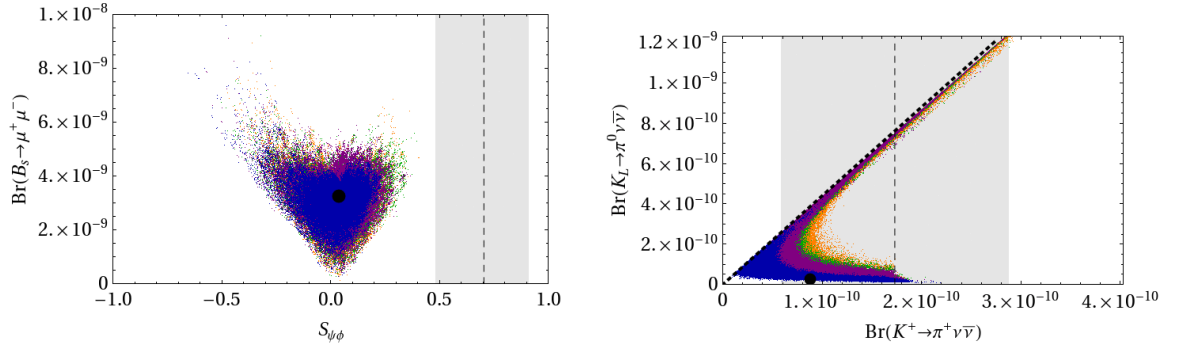


Figure 4: The correlation $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ vs. $S_{\psi\phi}$ (left panel) $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ as a function of $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ (right panel) after including the ε'/ε -constraint (colour-coding according to Tab. 2).

$\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ vs. $S_{\psi\phi}$ and $\text{Br}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ vs. $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ for the four different scenarios for the unknown hadronic parameters R_6 and R_8 . Note that for all scenarios the allowed range for $0 < S_{\psi\phi}$ is severely constrained. This behaviour can be easily understood; for $S_{\psi\phi} > 0$ the contributions from the Z^0 penguins with t and t' have the same sign and overcompensate the contributions of the QCD penguins. The solution to this problem is to reduce the effect of the Z^0 penguins while increasing the importance of the QCD penguins, e.g. the 'orange' scenario.

3 Lepton Flavour Violation

The mixing between the fourth and the first three lepton generations is stringently constrained through an interplay of radiative μ and τ decays and their respective

R_6	R_8		R_6	R_8	
1.0	1.0	dark blue	1.5	0.8	purple
2.0	1.0	green	1.5	0.5	orange

Table 2: Four scenarios for the parameters R_6 and R_8

tree-level decays [13, 12]. New experiments for the search of the decay $\mu \rightarrow e\gamma$ and $\mu - e$ conversion in nuclei are in the progress of being build or in a planning stage. On the left panel of figure 5 we show how these future measurements will constrain the correlation of $\mu \rightarrow e\gamma$ and $\mu - e$ conversion in nuclei. Note that the correlation is

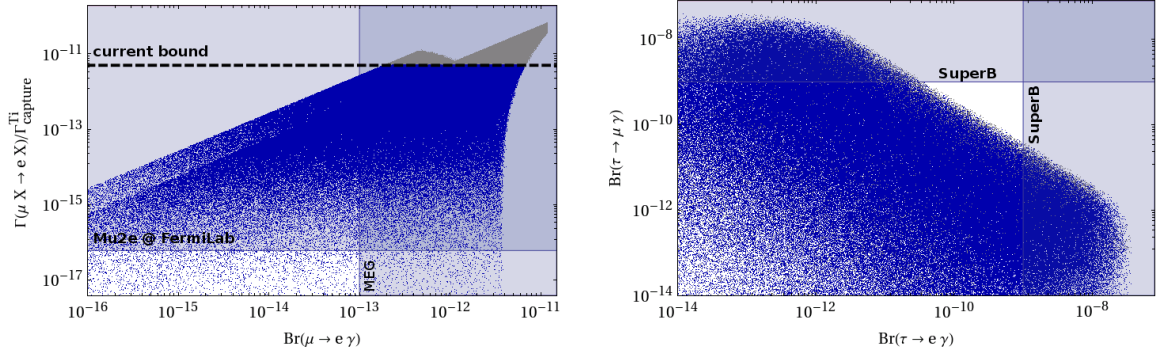


Figure 5: Correlation between $\text{Br}(\mu \rightarrow e\gamma)$ and $\text{R}(\mu\text{Ti} \rightarrow e\text{Ti})$ (left panel). Correlation between $\text{Br}(\tau \rightarrow \mu\gamma)$ and $\text{Br}(\tau \rightarrow e\gamma)$ (right panel). The shaded areas indicate the expected future experimental bounds on both observables.

rather diffuse, this is due to the fact that for $\mu - e$ conversion several contributions can cancel each other [12]. On the right panel of figure 5 we show the correlation between $\text{Br}(\tau \rightarrow \mu\gamma)$ and $\text{Br}(\tau \rightarrow e\gamma)$ together with projected exclusion limits from SuperBelle. The shape of the correlation is due to the $|U_{\tau 4}^* U_{e 4}|$ dependence for $\tau \rightarrow e\gamma$ and the $|U_{\tau 4}^* U_{\mu 4}|$ dependence for $\tau \rightarrow \mu\gamma$. Taking into account that $\mu - e$ conversion constrains $|U_{\mu 4}^* U_{e 4}|$ it is clear that $\text{Br}(\tau \rightarrow \mu\gamma)$ and $\text{Br}(\tau \rightarrow e\gamma)$ can not be at their maximum simultaneously.

4 Conclusions

- The branching ratio $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$ can be enhanced or suppressed in the SM4. However if $S_{\psi\phi} \gg 0$ as suggested by the Tevatron data was indeed true we would expect an enhancement of $\text{Br}(B_s \rightarrow \mu^+ \mu^-)$.

- In the K system there is independently of the B system much room for in some cases huge effects, however they are correlated among each other.
- ε'/ε can pose a very stringent constraint on the SM4 if the non-pert. parameters B_6 and B_8 were known to a decent accuracy.
- The new mixing angles in the lepton sector are tightly constrained through upper bounds on rare decays and tree level decays of μ and τ . Still big enhancements of rare decays are possible though not always simultaneously.

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